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Miriam: Welcome back to Great Mysteries of Physics from The Conversation. I'm Miriam Frankel, and I'm your host for the series.

What's the difference between a rock and a tortoise? Well, there are many, but what is it that makes the tortoise living and the rock inanimate? They are after all, just made up of a bunch of atoms, and the truth is we don't really know yet. Life seems to somehow just emerge from non-living parts.

What we know about the physics of the living world is slightly strange. It seems to contradict the second law of thermodynamics stating that a closed system gets more messy over time, increasing in what physicists call entropy, and that's what's responsible for the fact that you can mix milk into your coffee but you can't separate the two once mixed.

But this doesn't seem to be the case for living systems. A messy lump of tissue in the womb, for example, can grow into a foot with five toes, and that's a highly ordered state with low entropy, the opposite of what you might expect to get from thermodynamics. Similarly, nutrients can be pumped in and out of cells to create higher or low concentration in a way that is highly ordered too, rather than the nutrients being evenly spread out.

Because that's what normally happens when entropy rises. If you put a bunch of gas molecules in the corner of the box, for example, they would spread out over time. This episode will explore the mystery of life and some attempts from quantum biology to information theory to solve it.

To get started, I spoke to Jim Al-Khalili, a broadcaster and Distinguished Professor of Physics at the University of Surrey in the UK. I started by asking him what exactly is the difference between dead and alive matter?

Jim Al-Khalili: In a nutshell, that is the 6 billion, I don’t know what, big number from the question because I, I don't think, you know, if scientists are honest, we can't really say for sure. You know, take an example of a live mouse and a recently deceased mouse. You know, they have the same complexity. Uh, what is it that distinguishes animatematter from inanimate matter of the same complexity? And a lot of scientists in different fields will have answers as to do with energy flow or information flow or somehow maintaining order, low entropy we call it in physics, but we still don't really know what is it that, you know… how does chemistry become biology is a question we are still, we are still grappling with.

Miriam: I mean, it's not silly to think that that is something that physics should be able to tell us. What's the difference between a living and a dead mouse? Isn’t it?

Jim Al-Khalili: Everything's made of atoms and therefore, subject to the laws of physics and chemistry and the way atoms interact and stick together and make and break more complex structures. That happens inside the living cell in the same way that happens anywhere else in the universe. We know as, uh, as humans, you know, our life is finite and we grow older. Uh, so we will decay in the same way that inanimate matter decays. But we maintain this high sense of order for many, many decades. It's only when we die, that entropy, the second law of thermodynamics, then really kicks in and does what it needs to do.

So we are maintaining this highly ordered state. Now, that might lead us naively to think that we are nothing more than a steam engine. You know, that's often the example, a steam engine you, you feed it coal, a source of low entropy energy and it converts that. It enables it to do work, enables it to, to do something useful with it. Well, in a sense, that's what we are doing. We take in, well, plants take in sunlight and convert that into biomass. We eat those plants and we use that useful energy. To maintain order in our systems. So certainly that's what we are doing. But there isn't a similar example in the inanimate non-living world that does the same thing that can maintain this sense of order.

Miriam: Right. We did talk about this a little bit in the first episode and the concept of entropy and thermodynamics and how kind of the universe as a whole sort of entropy keeps rising. But it's almost like there are little pockets like us that kind of help enable that to happen as a whole. But we are sort of like weird exceptions.

Jim Al-Khalili: Yes, we are certainly, you know, we are a pocket of low entropy.

Miriam: Hmm.

What's surprising is that we are a pocket of low entropy that can maintain its low entropy. Overall, yes, the entropy of Earth plus sun, for example, the entropy is increasing. Um, so it's not that entropy is the same everywhere. What's surprising is that we can maintain this low entropy, we can use it.

Miriam: So there is a concept in physics called emergence that often gets cited when we don't understand something. You know, that some say that maybe our sense of time emerges from a timeless universe or you know, things like temperature can emerge from many particles moving together and stuff, you know, something similar must have, sort of, happened for life, for the first sort of cells to emerge. You know, what is this emergence thing?

Jim Al-Khalili: There are different definitions, what types of emergence, but usually what it basically means is that the whole is greater than the sum of its parts. There are simple examples, you know, like, um, think about the nature of water, the wetness of water. You could never hit upon the wetness of water by studying a single H2O or two or three or a dozen H2O molecules. That is a property of water that only emerges when you have trillions and trillions of water molecules coming together. And so it sort of goes against the idea of reductionism that, you know, if you want to understand something complicated, break it up into its constituent parts and see how they work and then you can fit them all together and you'll understand everything. Emergence says no, there are certain features of complicated systems that you would never be able to guess in advance of having the whole system there in place. And certainly when it comes to life, I guess, well, chemistry can start off very simple with organic molecules and they can build up gradually and complexity to make more complicated structures. But at some point, some structure must have become complex enough to be able to make a copy of itself, the very first replicator. And that emergent property replication, one can argue is the transition of chemistry to biology. Hmm. And we don't understand how, you know, we've got simplistic models of how something new emerges when you make it more and more complex. But when it comes to life, no, I don't think we have the answers.

Miriam: Sara Walker is an astrobiologist and theoretical physicist working as a Professor at Arizona State University in the US. She believes we shouldn't just focus on matter when trying to explain life. Ultimately, she thinks we need to broaden our minds and find a different way to construct a theory of life.

Sara Walker: So we've had this sort of history in physics of thinking about defining matter as the most elementary building blocks. When you get to the phenomena of life, that gets quite hard because life is this thing that we call an emergent property. So it's certainly not a property. So what that means is no atom in your body is alive, but you as an organized system are alive. And so this causes some problems that we don't have this sort of material description of what life is because it's something about the interactions of many pieces of matter as currently defined. Um, and I think part of the feature that's missing is that we talk about matter in terms of size or its mass, but we don't actually talk about matter as also having a property of having a physical dimension in time. And when you get to living matter, all of that complexity is built up over time. So if you start treating time as an explicit property, there become new ways of thinking about what matter is in life in terms of the complexity generated when you have information built up over time to make these more complex structures.

Miriam: So what is life exactly? I mean, you said before that life is an emergent property, so where does life come from?

Sara Walker: It seems like we know living things are obviously alive. That's sort of a canonical definition, but none of their parts are. So it seems like there should be some magic moment where life springs into animation and, you know, starts to do all these sort of magical properties, we associate it with agency and, uh, goal directed behaviour and all the things that we think are interesting about life. And there has been a long tradition of people trying to define life in terms of assumed basic properties, like living systems are capable of self reproduction or they have an organised metabolism. So for example, we have to eat in order to keep living. And all of these properties, kind of, you know, they have a grey boundary between what we might wanna consider life and non-life. So no matter what definition of life people have come up with, there's always exceptions to that definition. This is one of the reasons people always bring up viruses because they kind of half fit the definition and half don't. So what happens to really try to understand life is to recognize that we might actually need a deeper theory to actually bridge non-life and life.

Miriam: There seems to be three main approaches to understanding life with physics. One is based on thermodynamics, which normally applies to systems that are in equilibrium. Think, for example, of a cup of tea cooling down to room temperature by the well-balanced thermodynamic flow from hot to cold as entropy rises.

But we don't have a good understanding of the thermodynamics of systems that aren't in equilibrium, which is the case for living organisms. So this entire branch of physics, called non-equilibrium physics, may one day give us better tools to probe the physics of life. Another approach is quantum biology, which is based on the strange role of quantum mechanics governing the world of atoms and particles, and which Jim will describe in a minute. And the third method favoured by Sarah, has to do with using information theory to create a whole new physical theory of life.

Sara Walker: So there's a whole bunch of different theories that come from different places, but the whole enterprise of physics is to try to find that deeper explanation. And those are the three leading candidates that we have. Now, I'm in this sort of informational based perspective on it because I really do think that life mandates new physics. And if you look at our theories of thermodynamics or you look at our theories of quantum mechanics, they were really developed as fundamental theories for very different parts of reality than what we see as being the most prominent physics in life. So I don't, I don't think that those theories actually capture the regularities that we're really trying to understand. And I think there's been this assumption that we know all the fundamental laws and therefore we should take some that currently exist and apply them to life. And I think that's very premature. And I think it's not actually contextualising the problem of life in the history of physics and, and what we've seen in the past with major revolutions in our understanding of physical laws.

Miriam: Jim, however, believes that quantum mechanics may indeed hold a key to understanding life. And some argue that quantum mechanics is intimately connected with conscious experience, as we discussed in the previous episode. So while quantum systems may be in many possible states at once in a superposition, they randomly pick one when we observe them. So I asked Jim if it is this particular feature that is making physicists suspect that quantum mechanics can explain life.

Jim Al-Khalili: I think … My answer is no. That's certainly not what I mean when I think of quantum biology, when we talk about consciousness, there's often two ways where it comes into discussions of quantum mechanics. One is, as you mentioned, the idea that conscious observer can influence a system when they make the observation and gain information about it. And the other is that consciousness itself might be quantum mechanical. I think both those scenarios are not what we mean when we think about whether quantum mechanics plays a role in life. Certainly you don't have to have a conscious observer to make a measurement. We've learnt in the past half a century from studying an area called decoherence theory that anything can make a measurement.

Miriam: Decoherence is the word used to describe what happens when a superposition is broken and a random outcome is measured. But why do some physicists believe that quantum mechanics may be at the heart of life?

Jim Al-Khalili: First of all what quantum biology isn't is the fact that somehow life uses quantum mechanics in the way the atoms fit together and, uh, make organic molecules. After all, you can think of systems as complex as living systems. They will also utilise quantum mechanics in the same way you know, so it's not that we are made of atoms, and atoms behave quantum mechanically, therefore we behave quantum mechanically. Everything's made of atoms. But it is the notion that life has evolved the ability to appreciate the existence of quantum mechanics, to utilise quantum mechanics to its advantage. You know, evolution has had long enough to fine tune things or to stop quantum mechanics from doing something that life doesn't want it to do. And so it's a newish area of science. I mean, those arrogant physicists who in the 1920s developed quantum mechanics, certainly many of them believe that quantum mechanics was that magic extra that was needed to explain life. I don't think that's the case, but I certainly believe it looks like there are phenomena and mechanisms going on down at the molecular scale inside living systems inside the cell that only work because of quantum mechanics. So this brings together physicists, quantum physicists, quantum chemists, and molecular biologists.

It's interesting because it's a new area that is still speculative. And what's wonderful about those who work in it, and I include myself in that category, is that physicists don't like to get involved in biology. ‘Cause biology is messy and it's hard and it's complicated and you can't tweak dials and control things inside the living cell like you can in your laser lab for example. The biologists don't know quantum mechanics, so they say, well, no, it's don't be ridiculous quantum mechanics, all that woowoo nonsense, not in my lab mate. And then the chemists who sort of sit in the middle say, well, look, you know, everything's chemistry in the end and chemistry is quantum, you know, what's, what's all the big fuss? Why are you inventing new fields of science and calling it quantum biology you know, when it's just chemistry? So there's scepticism in the scientific community, which is nice for those who are working in this field because it means the field isn't too busy, too crowded, just yet. But there are some very interesting things that are happening at the moment that we are discovering.

Miriam: Yes and that's what I would like to hear next. So what kind of advances have been made recently? How far have we come?

Jim Al-Khalili: Well over the last few decades there have been some very clear examples that, for example, enzymes though the workhorses of the cell that act as catalyst to speed up their biochemical reactions in the cell, utilise quantum tunnelling.

So when they're making and breaking molecules, they are able to move particles around very much more efficiently than just classical mechanics would suggest. So they're getting particles A to B, electrons and protons, through quantum tunnelling, which is a quantum phenomenon. It's like passing a particle through an energy barrier that it doesn't have enough energy to get through. But in the quantum world, it tunnels through like a wave. It's like a ghost walking through a wall.

We are very familiar with quantum tunnelling in physics and chemistry, and lots of examples out in the world that use quantum tunnelling. What's surprising is that it can happen inside a living cell, because mentioned earlier about measuring a system and forcing it to stop behaving quantum mechanically, when you observe it. Well the cell is observing itself, the cell is carrying out measurements on these particles moving around, and the cell is a very hot, noisy, complex environment where what we call decoherence should take place very, very quickly. But what seems to be happening is that life has had three and a half billion years to perfect, to fine tune the mechanisms inside the cells in order to maintain these quantum effects like quantum tunnelling for long enough for them to have a biological function.

Photosynthesis is another example, still controversial, whereby the plants or bacteria use sunlight, absorb the particle of sunlight and deliver it to the reaction centre in the cell where it can be used as chemical energy. And it does that with efficiency far beyond what we might expect of a lump of energy just randomly bouncing around, which should just be lost as waste heat. So there's a quantum mechanical explanation for how that photon follows multiple paths simultaneously.

Miriam: There are some other examples too, aren't there? Like how birds navigate?

Jim Al-Khalili: The bird navigation one is the poster child of quantum biology only because it's so cool.

Miriam: Yeah.

Jim Al-Khalili: It's, it's such a, so we've known for, for, for since the 1970s that birds and other animals can sense the orientation of the earth's magnetic field. So this is what's called magneto reception. What the mystery has been, where is that compass? Where is that chemical compass inside the animal's body that gives it the information? And, the, uh, example that has been most studied is the European robin, which migrates from Northern Europe down to the

Mediterranean, every Autumn following the earth’s magnetic field orientation. And it seems that it does it through some process in the retina in its eye because it's light activated. And really the only explanation, the only theory in town at the moment is one that relies on what's called quantum entanglement. Essentially, that photon of light that comes into the bird's eye hits an atom inside a protein called a cryptochrome. The cryptochrome, these are light sensitive molecules. And that photon knocks one of a pair of electrons away from the atom that they're both sitting on. So these two electrons are now far apart, still within this protein molecule, but they're still quantum entangled. And the way they spin, the way they dance relative to each other is very sensitive to the orientation of the bird in the very weak magnetic field of the earth.

So quantum entanglement, this thing that Einstein didn't like at all, he didn't believe it, could be the reason why animals can navigate in the earth’s magnetic field. You know, quantum entanglement, helping the European robin find its way south is a sort of romantic explanation, which is, you can understand why it's become popular.

Miriam: Quantum biology is an ongoing process. In recent research, for example, Jim and his colleagues have used it to try to understand DNA mutations, a core part of life.

Jim Al-Khalili: So the idea that proton tunnelling might play a role in DNA mutations goes back half a century. The Swedish physical chemist by the name of Per-Olov Löwdin had a hand wavy paper where he said, you know, it could be so with the double strands of DNA, the double helix are held together by hydrogen bonds. So if you think of it as a twisted ladder, the hydrogen bonds are the rungs of the ladder and they hold together the bases on the DNA and we know the alphabet of life, the four bases A, C, and G. Uh, so A bonds normally to T and C to G, and they're held together by these hydrogen bonds, which are basically protons, they provide the glue that can hold the strands together. And Löwdin had suggested that those protons can jump where they're closer to one strand of DNA, where they feel more stable, more comfortable, more energetically favourable, they could spontaneously jump across to the other side. And they could do that just randomly. They could do that through quantum tunnelling. They could do that because a water molecule knocks them across. They may bounce back again. But at any given time, some small fraction of these proteins will be on the wrong side of the bond.

Miriam: So quantum tunnelling, does that mean it would sort of be at both places at the same time?

Jim Al-Khalili: Yes. So it'll behave quantum mechanically, and then if you measure it, or if the cell measures it, then there's a certain probability you'll find it on one side and a certain probability you'll find it on the other. Now, what happens in DNA is the thing that measured it, the equivalent of the human opening Schroedinger's cat's box is an enzyme called the helicase.

And what it does is unzip the two strands of DNA like a zip fastener, and when it separates them, that forces the proton to be on one side or the other. It can't be in both anymore. And then when these single strands of DNA get replicated at the other end at the replication process, if that proton is in the wrong place, that will lead to a mutation because C will no longer bond to G and A will no longer bond to T.

So it could lead to a mutation, which is very important. Our research now involves theoretical physics, computational chemistry, and molecular biology, and we are realising there's, again, because it's biology, there's layer upon layer of complexity. The probability that a proton is in the wrong place, just in DNA, that's in thermal equilibrium with its environment is not the same as the probability that you'll find the proton in the wrong place when it unzips, because lots of things happen. But it looks like in this case, and I'm speculating here because this is just my ideas as our team are coming up with these results, is that rather than life using quantum mechanics to its advantage, in this case, quantum tunnelling seems to be very, very important in getting the proton over to the wrong place, causing a mutation. Life doesn't want that. So what these enzymes are doing, are correcting for it. They're putting the proton back in the right place in order to make sure there aren't more mutations than there should be. But you know, every time we think we have an answer, we do another calculation and realise there's another layer of complexity that flips the answer over to something else.

Miriam: Yeah. Okay. I mean, normally when we look at objects in the microscopic world, like you know, humans or big rocks or whatever, we don't see any quantum effects. They're not in several places at the same time. So if there can be quantum effects in living systems, even though all we have all these atoms that all sort of measure each other, interact with each other, I mean, what's going on then in the boulder over here, that's also the same size?

Jim Al-Khalili: Well, the difference here between life and non-life is that living systems are really the only systems of this sort of complexity made up of trillions of atoms where the behaviour of a single quantum entity, like a proton quantum tunnelling across to the wrong site on DNA. Can have macroscopic effects. If it leads to a mutation, that is something that can get amplified. You can't get that in an inanimate matter. Everything just gets averaged out and washed out and doesn't have a macroscopic effect. But in life, you can have a single particle causing something that has a major influence down the line.

Miriam: As you've said several times, this is quite speculative, you know, what would it take to have some proof, I suppose, that this is how living systems behave. I mean, what, what would convince the majority of researchers?

Jim Al-Khalili: Well, experimental evidence, I mean, that's the problem with this field, that a quantum physicist like me can write lots of pretty equations and make predictions and then, you know, I'll work with a computational chemist who will have some sophisticated molecular dynamic simulations that shows how these molecules are behaving.

But when you want to go into the wet lab in a biology lab, and in a Petri dish and try and do an experiment to see, then it's really difficult because you, unlike in a physics lab, if you want to see how something behaves, you turn off all the other effects. You do your experiments near absolute zero. You do it in a vacuum. You shield your apparatus and instruments from outside disturbances. You can't turn those dials off inside a living cell. There are ways of doing experiments. So for example, if it were the case that proton tunnelling in DNA were very important, then if those mutations taking place say in bacteria in e-coli, you could envisage growing those bacteria in deuterated water. So water that has heavy hydrogen, you know, H2O D2O, so deuterium rather than the normal hydrogen with just a proton nucleus, heavy water has a much heavier nucleus because it's a proton plus a neutron. Now, quantum tunnelling is essentially, it's not a hydrogen atom, it's just the proton. It's just the nucleus of the atom.

If it's grown in deuterated water, then many of these hydrogen bonds in the structure, the DNA of these bacteria, should be made up of deuterium, deuterons rather than protons, which are twice the mass. And we know in quantum tunnelling in physics that if you double the mass, you decrease the probability of quantum tunnelling dramatically by many orders of magnitude. So what we should see if quantum tunnelling is causing mutation is a huge drop in the mutation rate. So that would be one example.

Miriam: And is anyone trying to do that?

Jim Al-Khalili: Well, we are already trying to. And we are seeing some evidence that mutation rate is dropping, but the questions are, for example, well, maybe mutation rates aren't that high anyway. Maybe quantum tunnelling isn't so important because this helicase enzyme is making sure the proton isn't in the wrong place. And if we did see a drop in mutations, how do we know it's not due to some other mechanism? Maybe these bacteria just don't like growing in deuterated water and will refuse to mutate for a different physiological reason. So it's still, you know, it's not a definitive proof. We need to be more imaginative.

Miriam: But could this sort of approach explain consciousness? After all, there is no perfect explanation for it. Scientists have tried to model it, but it's proving complicated.

Jim Al-Khalili: I wrote a book a few years ago with my colleague Johnjoe McFadden, called Life on the Edge, and we went through each chapter, we looked at some aspect of quantum biology, starting from what is more firmly established, like proton tunnelling, uh, due to enzymes all the way to the more speculative ideas. And towards the end of the book, inevitably we had to deal with quantum consciousness. This is an idea, it goes back several decades, Roger Penrose, Nobel Prize winner, he developed a lot of the theory of about the Big Bang. And in cosmology, uh, teamed up with another scientist, uh, Stuart Hameroff, who's an anaesthetist. And between them, they came up with this idea that consciousness is triggered, is switched on, due to quantum mechanics. Now they are still working on this area, papers are still being published on it. Most physicists are sceptical. They say, look, consciousness is mysterious. Quantum mechanics is mysterious. It doesn't mean the two are connected. On the other hand, we can't rule it out. We can't say no, quantum mechanics doesn't play in consciousness. We don't fully understand consciousness yet.

Miriam: You are listening to Great Mysteries of Physics from The Conversation. And if you're interested in science mysteries more generally, I've got a host from a brilliant science podcast, New Scientist Weekly here to tell you more about it. His name is Rowan Hooper.

Rowan Hooper: Hi Miriam. Thanks for that. Yeah. New Scientist Weekly. It's the award-winning podcast from New Scientists magazine and we cover the essential science stories of the week and maybe some that aren't quite essential, but they will enrich your life. From breakthroughs in understanding how the brain works and the mysteries of consciousness to the latest on the climate crisis, to exploring the moons of the solar system, uh, to the anti-aging properties of urine. We've got it all! New Scientist Weekly is a free life-affirming dose of science, and you can find it wherever you get your podcasts.

Miriam: Maybe quantum mechanics has been crucial in the evolution of life, but Sarah doesn't think it will suffice as an explanation. She instead wants to build a whole new physics of life based on something called information theory, which takes information to be real and physical. And there's no doubt that information seems to be somehow crucial to life. Living organisms have an inbuilt set of instructions such as DNA, which can replicate, combine, and create new beings, which non-living things simply don't have. Similarly, when living beings invent things, they need information stored in their memory to do it. Like humans need a deep knowledge of the loss of physics to create the technology we use today. So there just seems to be something about life that relies on information.

Sara Walker: Yeah, so information theory is a potential way of thinking about life, but when I say information, I actually mean it much more broadly. And this is one of the things where it gets a little hand-wavy when you're trying to build new theories of physics because we have these words that we used to describe things, but the real reason that we need new explanations is because we don't understand the phenomena. So part of the reason that I think that we need new principles is that there are a few features of life that are really hard to understand. One of them is this kind of idea people have discussed for a while, which is like a notion of causation at higher scales. So the fact that your thoughts actually seem to have some consequences in the world seems very paradoxical from the standard perspective of physics because your thoughts are not features of your atoms. It again, goes to this kind of idea of emergent properties. They're features of the collection of neurons in your brain, and you can see, you know, features of these emergent patterns in living systems constraining and actually dictating their behaviour all across, you know, all the way from cells and you know what gene expression patterns, you have to, to human thought. So it's, it seems to be ubiquitous in life that we see information calling the shots, so to speak. And the other feature that I think is really important is this idea that some things that exist on our planet require acquisition of information in order for them even to ever happen.

And the examples I usually give for that are to think about launching satellites into space. You know, it's not forbidden by the current laws of physics, but you would never be able to predict from Newton's laws of motion that we'd be launching metal boxes into space. What that requires is actually, you know, evolved systems that have knowledge of Newton's laws of gravitation in order to build those boxes and launch them into space.

Miriam: So if you're just sort of like observing with a telescope, earth over time. You could sort of calculate what would happen if you knew all the starting positions of the bodies around and if something was gonna smash into it, yes, what's gonna happen over time and stuff like that. But you would never be able to predict that suddenly some humans would start putting satellites up and which satellites and how many and stuff like that. So it's something that is like, beyond normal physics. It's like a human being having an idea and doing it and changing the actual planet.

Sara Walker: Yes. So life seems to be doing this thing where it's building these very low probability structures, but it can do that because it's storing information collected over time. And we've had, you know, billions of years of evolution on this planet generating more complex structure and retaining memory of the past to build that structure. And so that feature to me is the most significant feature about what life is.

Miriam: So does Sarah think that there are yet to be discovered loss of life?

Sara Walker: Yeah, so I do think that there are laws of physics that are yet undiscovered that explain the phenomenon of life. And I think those have to do with how information structures reality in some sense. And that goes back to sort of this concept of redefining matter and thinking about time as a feature of complex systems. But the way that I approach that is I've been working with collaborators at University of Glasgow, uh, Lee Cronin's lab there, on this theory called Assembly Theory, which aims to quantify in some sense how much information is required to produce a molecule of a given complexity. And we really think that this might be a general theory of physics that just happens to emerge in the scale of chemistry.

Miriam: Chemistry relies on a set of elementary building blocks. Tiny particles known as quarks, make up bigger particles known as proteins and neutrons, which in turn make up the atomic nucleus. And when the atomic nucleus is surrounded by electrons, they become atoms.

Sara Walker: But if you take a step back just to think, then now we have atoms, we have the periodic table, what can we build out of that? And that's actually a huge combinatorial space. There are more, um, molecules of, uh, you know, I think if you take a standard size protein of a hundred amino acids and you try to make every possible one of them, it would fill, you know, not just one universe, but many universes full of molecules. Like there's no way to make every possible molecule. There's not enough time and resources in the physical universe to do it. And so if you think that the universe is trying to generate complexity, when it hits chemistry, there's this barrier where it's impossible to saturate every possible thing that the universe could generate. So what we think happens is there's some phase transition, so to speak, where information or selection becomes necessary if you see objects above that threshold. So in order to see complex objects in high abundance,which we have in abundance on earth, uh, you need to actually store information specific to that object and excluding all other objects that might be sort of similar complexity.

Miriam: A complex system, what could that be? Like a cell or?

Sara Walker: Yeah, or even a molecule. So, mm-hmm. We can go back for a second just to molecule. So I mentioned that we were trying to measure the amount of information. If we use a molecule, it's actually pretty easy to do that. If you don't like chemistry though, we can think about it with Lego, cuz that's a little bit easier. So think about the Lego universe, right? If I just dumped a thousand Legos on the table and I asked you to build a structure and I didn't constrain you at all, and you try to imagine all the structures you could build out of a thousand Legos, it's a lot of structure. That's the combinatorial diversity I'm talking about. And in fact, you couldn't build with, you know, the entire history of the universe, all possible Lego structure with a thousand Lego, there's not enough time and resources, right? Or you have the resources, but you don't even have enough time to go through and build every possible one. So that's what we mean by combinatorial space.

Now if you think about that for molecules, if you, you said you had a particular Lego object and I always like to use Lego Hogwarts cuz everybody knows what Hogwarts looks like and most people know Legos. So it's a good analogy. Let's say I smash Lego Hogwarts and I say let's rebuild Lego Hogwarts. We can start by taking, you know, some of the building pieces and, and joining them together and then taking a piece and joining it and taking a piece and joining it to things we built before and build up to Lego Hogwarts. And the way we measure how much selection is specific to Lego Hogwarts as an object you could form in our universe by the laws of Lego is to look at the minimal path to produce Lego Hogwarts. So that minimal path for Hogwarts is quite large because the object is very complex. If I just said, you know, stack three yellow blocks and three white blocks together. That's a very simple object and you probably would find that pretty quickly. And so we've got Lego Hogwarts with a very short, minimal path and this little stack of white and yellow Legos with a very short path. Now, if I started shaking the table with all the Legos on it, which one of those do you think would spontaneously form? Maybe a very low probability of the stack, but pretty much impossible for Lego Hogwarts. And so part of our conjecture is if you see something complex like Lego Hogwarts, and in particular, if you see multiple copies of it, so on our planet, it's not just that Lego Hogwarts where it's formed once, it's that there is, you know, a set of instructions in a box that people can go and buy and build copies of this object. That suggests that there was selection and evolution to actually build that specific structure, but it's encoded as a feature of the object.

So now we talk about this idea of these pathways for building the object that's the assembly space of the object, and it becomes a feature of how hard it is causally for the universe to produce that particular structure in terms of physical operations that you can implement to make it. And the thing that's super cool for molecules and why this becomes a testable theory of physics is you can measure that feature the the shortest path in the lab for molecules. So we can actually go into the lab, look at a whole bunch of molecules, and we can measure this shortest path feature of how they're built up by this recursive operation of joining and taking pieces we've made and then we can look and see are there any molecules with high complexity or high assembly that were produced by non-living things, and we don't see any evidence of that. We really do see this kind of threshold where if objects are sufficiently complex, we only see them in life because they require information and selection to produce them.

Miriam: So things that aren't alive simply aren't as complex or difficult to assemble from fundamental building blocks as living things are. And when you have even simple living things, they seem to generate even more complexity, either by evolution or by construction. Objects so complex that they couldn't exist before. So it seems life has generated a sudden boost in complexity, which may have some sort of a threshold that Sara believes could be a fundamental feature in the physics of life.

Sara Walker: So, for example, like Taxol’s an anti-cancer drug, we don't expect that to occur, in this theory of physics in particular, anywhere else in the universe. It's such a complex object, it requires the knowledge of an intelligent chemist to produce it.

Miriam: But even in the periodic table, there are some elements only humans can produce

Sara Walker: Yes, that's right. So life can produce low complexity objects also. And so you might have a false negative where you have something that was produced by life, but it's below the assembly threshold or the complexity threshold. But you'll never see objects that are high complexity produced abiotically. At least not in a high abundance. We don't have a theory of physics that deals with the combinatorial universe. What are all the structures that you can build up like the complex universe? And so this proposal is basically saying there has to be a transition at the origin of life to new physics that allows you to explain why you see some physical objects appear in the universe and not others.

So you see this through the entire history of life, that the objects that are produced can be made more complex because we're reusing things that we've made in the past. So the primary goal of this theory of physics is to predict when the origin of life should happen in chemistry. So when is it that you get an open-ended evolving system and can you measure that transition in the lab?

So our conjecture is that we'll be able to go in the lab and detect from a chemical system like. You know, you have robots guiding some chemical soup experiment and trying to select on different features. We'll be able to detect when the origin of life happened, um, because we'll be able to detect that we evolved a chemical system that can generate its own complexity in an open-ended way.

Miriam: If the experiments could detect when the origin of life happened, it would be a boost for the theory, and it turns out that could come in handy for astrobiologists.

Sara Walker: It also potentially has other implications because it might be possible, and I think this is possible to, number one, use it to detect life on other planets. So if you go to say a moon like Titan in our solar system, which is a moon of Saturn and it's a very exciting target for astrobiologists cuz it's got all this rich, organic chemistry happening on the surface of the moon. It's the only other body in our solar system that has a liquid on its surface. But Titan's really weird. It's not liquid water, it's a liquid gas. And so we think the chemistry is radically different. So you know the challenge going there is we don't expect earth-like chemistry to survive in that environment and be viable. So how would we build a measure that could allow us to detect whether you had a living system? And this is, this is one way of doing it because we can go in the lab and measure it. And what we're looking for is a chemical system that generated complexity through an evolutionary process.

Miriam: I see. Because typically, you know, physicists will look for life in the exoplanets and stuff to look for the signatures that are important for life here, like water, oxygen and stuff like that. So you are saying that there might be some completely other form of life, which we have no way of detecting because we don't have the physics for it. But you're trying to create a physics that could find any type of life.

Sara Walker: That's right. Yeah

Miriam: And so how close are you to having a ready baked theory of life then?

Sara Walker: I think we have the theory, we have some things we have to still work out as far as the implications. And this gets to the second part of your last question about what does it tell us about physics. Because if this theory is right, or on the right track, it suggests some really different kinds of physics than we have in our current theories of physics. And one of those features I already alluded to, which is that time becomes a material property. And the reason I say that is because if you think of a complex molecule, so in assembly theory, the universe is organised in layers of this depth and time. And the deeper in time an object is the harder it is to produce and the longer an evolutionary or selected pathway you need to produce it, and the rarer it would be with standard physics. So there's a way that we can talk in assembly theory about how you build up that structure of these objects becoming more complex in time, but you have to take time as a serious feature of the physics.

Miriam: Time and information?

Sara Walker: Time and information are kind of the same thing, and they're fundamental. So time is fundamental in this theory of physics. Uh, whereas in most theories of physics we've built so far, time is an emergent property and something the universe moves through. It's not a property of objects. And so another way of thinking about it is to think some objects require memory to make them so the universe actually has to remember it has to store that memory in other objects.

Now, if you think about something like an electron, you know, a very simple physical object, it doesn't require memory for the universe to make that. That's a spontaneous object. It can be produced with sufficient energy anywhere in the universe, right? As long as you have the right ingredients and you have the right energy. But something like you or I, we’re high memory objects, we require this entire lineage of information being built up over time. And the conjecture of our theory is that high memory objects have this intrinsic feature of time being a property of the object, and they're not describable by current physics.

Miriam: Okay, so you also said before that information is real so it's not something that we've invented. It's an actual physical thing just like a particle. Does that mean that kind of technology could be alive?

Sara Walker: Technology is life. It's just, it's just objects are deeper in time. So the deeper in time an object is, the more evolution required to produce it, the more informational it looks. And so this is one of the reasons, like digital worlds, you know, all the technologies we're building require life to evolve for three and a half billion years on this planet to achieve human level intelligence. To construct these devices so they don't appear for free in the universe. And all of that time then gets encoded in these technologies. But they're just very small volumes of space that have all of this history now in them. So the way I conceptualise artificial intelligence is really just a feature of another major transition in what life is doing as far as building structures that were built in the past, now at larger and larger scales.

Miriam: So although we don't really understand the fundamental physical basis that makes life so special, there’s certainly no shortage of ideas. Perhaps this is a mystery that we could one day crack thanks to quantum biology, assembly theory or non-equilibrium physics, or perhaps a combination of all of them.

Or will an ultimate theory of everything be needed combining different and clashing theories of physics? In the next episode, we'll talk about why it's so hard to unite our two best theories of physics, general relativity and quantum mechanics. We'll discuss topics including hidden dimensions, dark energy, and particle physics, asking whether physics, as we know it, is ultimately broken.

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